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Original Contribution

HUMAN-ROBOT COORDINATION IN INTELLIGENT WAREHOUSE SYSTEMS: AN ENGINEERING LOGISTICS MODEL FOR TASK ALLOCATION

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Abstract: *Intelligent warehouses increasingly operate as mixed sociotechnical environments in which human operators, autonomous mobile robots (AMRs), information systems and material flows interact in real time. The central engineering question is therefore not whether robots should replace humans, but how tasks should be allocated so that operational performance improves without creating unacceptable physical, cognitive or safety burdens for workers. This conceptual study synthesizes recent research on human–robot collaboration in warehouses and proposes the HRT-A (Human-Robot Task Allocation) model. The model considers physical workload, cognitive complexity, safety relevance, spatial dynamics, urgency, the need for human judgement and expected logistics performance. It comprises five stages: task description, assessment of human workload, assessment of robotic suitability, selection of the executor and feedback. HRT-A is intended as a decision-support framework rather than as a validated optimization algorithm. Its contribution is to connect task allocation with human factors and warehouse performance while explicitly accounting for dynamic reassignment and responsibility when exceptions occur.*

Key words: ***E****ngineering logistics, Intelligent warehouse, Human-robot collaboration, Autonomous mobile robots, Task allocation, Human factors, Order picking.*

1. Introduction

Warehouse automation has shifted from isolated conveyor systems toward mobile, data-driven and increasingly autonomous technologies. Autonomous mobile robots are now used for internal transport, replenishment, order-picking support and material movement, while warehouse management systems coordinate tasks and routes. These technologies change the content of human work rather than eliminating it. Human operators continue to handle exceptions, quality control, contextual judgement and communication, and they often work in the same spatial environment as mobile robots [1, 2].

Recent studies increasingly treat warehouse human–robot collaboration as a sociotechnical problem. Zheng, Glock and Neumann show that the performance of such systems depends on the interaction of technology, tasks, human factors and system outcomes, while the effects on workers remain less extensively studied than technical performance

outcomes [3]. Experimental work on collaborative order picking indicates that robotic assistance can reduce physical workload and improve some aspects of working posture, although the effect depends on layout, team configuration and task design [4]. These findings support a task-allocation perspective rather than a simple drive towards maximum automation.

The aim of this paper is to propose a conceptual engineering-logistics model for allocating tasks between human operators and AMRs in intelligent warehouses. The object of study is the mixed human–robot warehouse system; the subject is task allocation under physical, cognitive, safety, spatial and performance constraints. The working proposition is that warehouse performance depends not only on the level of automation but on the quality of coordination between human and robotic resources. The HRT-A model developed below is conceptual and requires subsequent empirical validation.

2. Related work

AMRs are attractive in warehouse environments because they can reduce repetitive walking and transport effort and can be deployed without fixed guide-path infrastructure. A recent review of warehouse AMRs highlights their growing feasibility and their potential to reduce time and effort in repetitive internal transport [2]. At the same time, human exposure to moving robots creates additional requirements concerning perceived safety, trust, predictability and communication. Haney and Liang identify robot behaviour, approach speed, path predictability and worker trust as relevant human-factor variables in industrial AMR interaction [1].

Warehouse coordination has also been studied from an operational perspective. Multi-agent approaches model warehouses in which human pickers and mobile robots must coordinate movements and actions in order to improve pick rates and reduce congestion [5]. Research on mobile robot fleets similarly identifies task allocation as a central management problem because assignment decisions influence energy consumption, fleet size and economic and environmental performance [6]. Such studies are valuable, but they typically optimize system-level objectives and do not by themselves determine which tasks should remain human, which should be robotic, and which should be performed collaboratively.

The ergonomic dimension has become more visible in recent work. Zhang et al. compared manual and robot-assisted order picking through laboratory measurement and simulation and found evidence of reduced human workload under collaborative configurations [4]. This strengthens the case for treating workload and safety as explicit allocation criteria. The present study builds on this literature by developing a compact engineering-logistics framework in which human strengths, robot suitability and logistics outcomes are considered jointly.

3. Problem description and methodology

Task allocation is treated here as a multi-criteria engineering decision. The unit of analysis is the operational warehouse task rather than the worker or robot as an indivisible resource. For each task, the decision maker identifies the material to be handled, the route, timing requirements, quality constraints and likely exception conditions. The task is then assessed from the standpoint of human workload and robotic capability. No universal numerical weights are introduced, because their validity would depend on the specific warehouse, robot platform, operating regime and workforce.

The criteria used by the HRT-A framework are summarised in Table 1. They are intended as diagnostic prompts. A robot is not automatically preferred because a task is

repetitive, and a human is not automatically preferred because a task is complex. Technical feasibility, safety requirements and exception handling remain boundary conditions.

Table 1. Diagnostic criteria for human–robot task allocation

Criterion	Human suitability	Robot suitability
Physical workload	light, varied or dexterous work; manageable exposure	repetitive transport, load carrying or physically demanding movement when technically feasible
Cognitive complexity	context judgement, adaptation, ambiguous information, exception handling	structured and repeatable decision logic with reliable data
Safety relevance	human verification or judgement when required by the task	hazard exposure may be reduced when robotic execution is technically safe and validated
Spatial dynamics	highly variable or partially unstructured environments	mapped and controlled routes with predictable obstacles
Urgency	unplanned events requiring rapid contextual judgement	scheduled and repeatedly optimised missions
Quality	visual inspection, exceptions and non-standard defects	standardised operations with low variability and measurable acceptance criteria
Responsibility	decisions with safety, quality or customer consequences	execution of authorized and predefined instructions

The HRT-A procedure consists of five stages: (1) task description; (2) assessment of human workload, including physical effort, cognitive complexity and time pressure; (3) assessment of robotic suitability, including payload, route, sensing and environmental constraints; (4) selection of a human, robot or collaborative execution mode; and (5) feedback based on time, errors, waiting, safety observations and operator experience. The feedback stage makes the model iterative rather than a one-time classification.

4. Conceptual results and discussion

The principal outcome of the conceptual analysis is the HRT-A model shown in Table 2. Its purpose is to make task-allocation reasoning explicit before an automated workflow is adopted. In practice, the same task may move between execution modes. A transport mission may be assigned to an AMR under normal conditions but reassigned to a human operator when an aisle is blocked, the data are inconsistent or the handling unit is damaged.

Table 2. Five-stage HRT-A model

Stage	Main content	Decision output
1. Task description	operation, load, route, frequency, quality and timing requirements	explicit task definition
2. Human-workload assessment	physical effort, cognitive complexity, time pressure, exposure	human-factor constraints
3. Robotic suitability assessment	payload, navigation, sensing, environment, interface requirements	technical feasibility
4. Executor selection	human, robot or collaborative team	allocation decision
5. Feedback and reassignment	time, errors, congestion, safety observations, operator feedback	continuous improvement and dynamic reassignment

Poor coordination can produce four groups of effects. First, operational losses arise through waiting, empty travel, route conflicts and underused capacity. Second, safety risks increase when robot paths, speed or stopping behaviour are not sufficiently predictable to workers [1]. Third, cognitive and organisational load may increase when operators do not understand the automation logic or do not know who is responsible during an exception. Fourth, over-automation may transfer decision tasks to people without providing the information, time or authority required to manage them.

The model therefore adopts a human-centred principle of automation: robotics should support human performance rather than simply remove human activity from the process. This position is compatible with the sociotechnical interpretation of warehouse collaboration [3] and with evidence that collaborative configurations can reduce physical workload when the system is appropriately designed [4]. It also implies a need for adequate training, intelligible interfaces, reliable emergency-stop procedures and clearly assigned responsibility for exception handling.

The study has limitations. HRT-A is a conceptual framework and not a validated scheduling or optimisation algorithm. It does not yet include empirically determined weights, thresholds or productivity coefficients. It should therefore be tested in pilot warehouse processes and compared with existing allocation practices. A future study could combine expert content validation with time-motion data, congestion indicators, ergonomic assessment and operator-reported workload.

5. Conclusion

Human–robot coordination is becoming a core engineering-logistics issue in intelligent warehouses. The relevant design problem is not the maximum attainable automation level but the allocation of tasks to the resource that can perform them safely, reliably and efficiently under the actual operating conditions.

The proposed HRT-A model structures this decision through five stages and explicitly combines human workload, robotic suitability, safety and logistics performance. Its main contribution is a transparent task-level framework that preserves human judgement and responsibility while using AMRs where they provide real operational value. The model is suitable for subsequent expert validation and pilot application, but its practical effectiveness must be demonstrated empirically before quantitative thresholds or generalised allocation rules are proposed.

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